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A Future Vision of Data Acquisition: Distributed Sensing, Processing, and Health Monitoring

Fernando Figueroa, Wanda Solano, and Charles Thurman
NASA Stennis Space Center, Test Technology, Stennis Space Center, Mississippi, USA

John Schmalzel
Rowan University, Department of Electrical and Computer Engineering, Glassboro, NJ, USA

Abstract – IEEE Abstract

This paper presents a vision for a highly enhanced data acquisition and health monitoring system at NASA Stennis Space Center's (SSC) rocket engine test facility. This vision includes the use of advanced processing capabilities, in conjunction with highly autonomous distributed sensing and intelligence, to monitor and evaluate the health of data in the context of it's associated process. This method is expected to significantly reduce data acquisition costs and improve system reliability and accountability. A Universal Signal Conditioning Amplifier (USCA) based system, under development at Kennedy Space Center, is being evaluated for adaptation to the SSC testing infrastructure. Kennedy's USCA architecture offers many advantages including flexible and auto-configuring data acquisition with improved calibration and verifiability. Possible enhancements at SSC may include multiplexing the distributed USCAs to reduce per channel costs, and the use of IEEE-485 to Allen-Bradley ControlNet gateways for interfacing with the resident control system.

Keywords – Data Acquisition, Intelligent Sensors, Propulsion Testing, Health Monitoring, IEEE 1451.

I. INTRODUCTION

Stennis Space Center, in Hancock County, Mississippi, is NASA's lead center for rocket propulsion testing. Data acquisition is central to the ability to provide facility resources, control tests, and provide the means to analyze performance. Sensors used for data acquisition and control fall into two general categories: facility or test article. Facility sensors refer to those used in conjunction with the propellant delivery and thrust measurement systems. These sensors are generally considered to be an integral part of the "test stand" data acquisition and control system. Test article sensors refer to those used to monitor the behavior and performance of the engine or device under test. These sensors are configured into the resident data acquisition and control system as needed and required for each particular engine test program.

The propulsion test environment shares many features in common with the data acquisition requirements of industries including manufacturing and process control. Reconfiguration of data acquisition elements is required in preparation for new tests and processes. Of continuing interest are those techniques that can help reduce the personnel costs needed to reconfigure systems to identify and rectify problems and meet new requirements. Another critical need is improvements in the quality and reliability of measurements—i.e., monitoring the health of the data acquisition system.

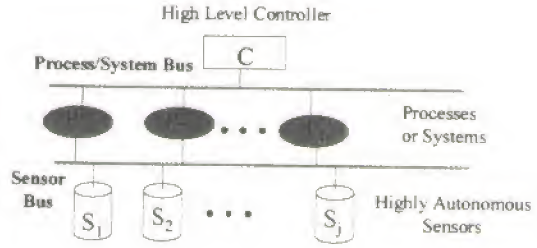

Figure 1. Sensor and Process/System Physical Taxonomy

A functional topology depicting the authors' vision of a future data acquisition (DAQ) system is shown in Figure 1. This topology will support a hierarchical system with distributed "intelligent" components. A Highly Autonomous Sensor (HAS), at the lower level, will encompass a front-end-electronics that is self-calibrating on a continuous basis. It also will have sufficient processing power to monitor its data in the context of the process that it partakes. So the sensor will send its data to the process, along with additional qualifying information. For instance, it may inform the process that the signal just experienced a "step change" at a rate appropriate for the process. The extraction of qualitative behaviors such as "step change" will be implemented using AI tools developed for "Qualitative Physics." At the process level, data and qualifying information from all HAS's associated with the process will be fused. The process will check for consistency based on models that may include qualitative physics, analytical equations, numerical models, statistical models, neural nets, genetic algorithms, etc. The process will also have a learning engine to capture consistent behaviors derived from the sensors that may not have been included in its knowledge and databases. At the higher level controller, information regarding all processes will be fused. The controller will check for consistency among processes and, again, will send control signals accordingly to improve the process

models and to ensure overall efficiency and integrity throughout the system.

The components of the system envisioned in Figure 1 are currently available commercially. One such element that may be used as the platform for the HAS is the universal signal conditioning amplifier (USCA) developed at Kennedy Space Center (KSC) [6]. It is being evaluated for adaptation to the SSC testing infrastructure. This paper outlines data acquisition requirements, health monitoring needs and possible solutions, the USCA as a candidate platform for a HAS, and the evaluation steps that have been undertaken and that are planned for this platform. The primary focus is to determine system design modifications that would provide enhanced flexibility, reduced costs, and include health monitoring. Results should be of interest to a variety of data acquisition users.

II. DATA ACQUISITION SYSTEM REQUIREMENTS

Typical data acquisition system (DAS) environments such as SSC need to combine a large number of general- and special-purpose transducers [1]. For example, pressures (high, low), temperature, force, flow, mass, optical, radiant, acoustic, etc. A variety of techniques are employed. Direct interfaces require traditional signal conditioning amplifiers. Smart transducers include local signal conditioning and operate over 4-20 mA current loops. Any flexible DAS should provide the ability to mix both types of transducers. Table 1 suggests some possible combinations. In addition, the DAS must provide time stamped deterministic data for use by control system and for permanant storage. Finally, calibration data should be easily acquired and applied.

Table 1. DAS Transducers

Channel	Variable	Specifications	Transducer Type
0-50	Temp.	Cryogenic, low bw, low sps	Thermocouples
51-65	Pressure	3000 psi, high bw, low sps	Strain gage bridge
66-100	Pressure	300 psi, low bw, low sps	Strain gage bridge
101-105	Flow	1000 l/min, low bw, low sps	4-20 mA
106	Force	750,000 lbf, low bw, low sps	Strain gage bridge
107-150	Accellera-tion	± 50 g, high bw, high sps	Piezoelectric sensor
151-165	SPL	20-20kHz, high sps	Microphone

III. HEALTH MONITORING

Health monitoring is one area that could directly impact the cost/benefit of a data acquisition system. The objective is to have a monitoring system that continuously determines if a sensor is operating appropriately within the context of the monitored process. This can provide the framework for determining out-of-calibration, drift, lost power, or other fault conditions. It can also serve to help predict future failures. Other potential benefits of such a monitoring system include reduction in false alarms and avoidance of unnecessary maintenance and shutdowns. Enhanced system integrity could be achieved, combined with faster and more effective diagnostics when problems arise. Finally, system documentation would be improved, which enhances quality control.

There are two primary approaches to the development of health monitoring systems: (1) Bayesian statistics applied to networks of components, and (2) qualitative modeling methods. Both approaches involve sensor fusion, since relationships among values of sensors are crosschecked.

NASA has used the statistical approach to develop real-time sensor validation methods for propulsion systems [2] and autonomous flight control [3]. The basic Bayesian approach is termed "analytical redundancy." It is based on a crosscheck of analytical relationships among sensors and incorporates a voting scheme to determine if a sensor is operating properly. A strength of the method is that it can be done in real-time. One potential pitfall is that apparent inconsistencies in sensor behavior may actually be due to problems with the monitored process, and not necessarily imply sensor failure. Qualitative modeling involves two steps. First, qualitative relationships from the physical principles governing the process need to be extracted. Then, these relationships are evaluated to determine goodness of fit for the entire process. Qualitative relationships constitute a qualitative model composed of a set of symbolic equations. A complete theory of qualitative modeling has been developed [4]. Qualitative models permit analysis of a system by discrete components and at an intuitive level. It can help to pinpoint possible failing components for further in-depth analysis.

As an example of a qualitative relationship, consider the constraint for conservation of mass flow in a compartment given by

$$\text{flow1} + \text{flow2} = \text{flow3} \qquad (1)$$

A corresponding value set for this constraint might be

(flow1_high, flow2_nom, flow3_high) (2)

The relationship expressed in (2) specifies that when flow1 and flow2 are at their "high" and "nominal" landmarks respectively, then according to (1), flow3 should be at its "high" landmark. This method can be seen to combine both analytic completeness and conveys a strong intuitive sense of system behavior.

The highly autonomous sensor (HAS) approach [5] focuses on qualitative interpretation of behaviors associated with a sensor and its measurand. It concentrates on individual sen-

sors and does not include sensor fusion schemes. It is generic and permits instantiation of any sensor (new or existing) as a HAS with only a small amount of sensor/measurand specific data. HAS models are inspired by the intuitive approach of people who monitor signals from sensors. The model extracts qualitative behaviors from the raw data. For example, behaviors may be described as constant with noise, spike, high noise, ramp, drift, sinusoid, step change, disturbance, flat, etc. Once these behaviors are identified, they are analyzed to detect unusual conditions. The main components of the HAS model include a sensor database, a measurand database, a module to extract qualitative behaviors, and modules for sensor maintenance and learning. Learning is an attractive feature, since it instills self-evolution of the model.

With all sensors in the system defined as HAS's, high level, qualitative information fusion methods can be used to monitor and diagnose. Qualitative relationships such as in equation 2 can be further strengthened by the inclusion of qualitative behaviors provided by each HAS. In addition, other more generic approaches to intuitive information fusion can also be applied. For example, a common sense rule when monitoring signals associated with a process is that all signals experience a change in behavior at the same time. For example, if the temperature in a tank filled with gas experiences a step change, so should the pressure. If one of many sensors in the process breaks this rule, it can be quickly detected as faulty. Moreover, the behaviors of this sensor can be further analyzed to determine why it may be malfunctioning.

IV. UNIVERSAL SIGNAL CONDITIONING AMPLIFIER (USCA)

The USCA can be used to implement a highly flexible and reliable DAS. Figure 2 shows the block diagram of a USCA based DAS.

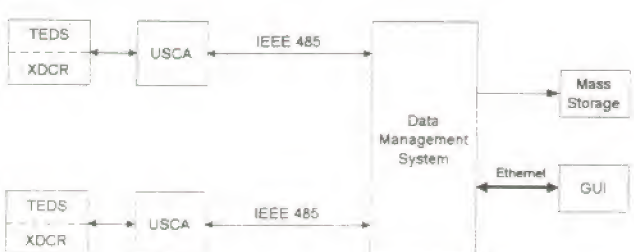

Figure 2. A typical USCA application consists of a transducer and its associated TEDS connected to a USCA. The collection of USCA outputs are fed to a data management system, which multiplexes, adds time stamping and fronts a general data acquisition environment for data display and management.

The USCA takes full advantage of high performance DSP chips and analog subsystems to implement high-performance data acquisition. The amplifier is configured for operation using information stored in the Transducer Electronic Data Sheet (TEDS) that supports IEEE 1451 [7]. The TEDS includes information regarding the transducer type, required excitation level, output voltage range, linearization coefficients, measurement identification number and others. Some of the features of the USCA include:

- Input and output self-configuration including programmable voltage or current excitation, gains, filtering, linearization and sample rates.
- Two independent channels for alternating I/O calibration and signal using a 1 ppm/ °C stable voltage and zero reference. Monitoring and self-adjustment of the excitation voltage or current. Self-diagnostics.
- DC-DC converters to achieve electrical isolation among the input power, the transducer, analog output and digital output.
- 16-bit sigma-delta analog-to-digital conversion.
- Programmable digital output maximum rate of 20 KS/s at 440 kbaud.
- Bridge auto-balance configuration.
- Meets Kennedy Space Centers Launch Processing System standards for vibration exposure as specified in KSC-STD-164.

V. USCA ARCHITECTURE ENHANCEMENTS

During the evaluation of the USCA architecture to meet SSC requirements, several possible modifications to the basic USCA architecture have been identified including:

- Multiplexed channels per distributed USCA amplifier to reduce the cost per channel. This is especially useful for low bandwidth transducers.
- Use of fiber-optic transmission from the test-stand multiplexers to the TCC.
- Addition of 4-20 mA sensor USCA amplifiers. Although the majority of the test article sensors are transducers, a small percent of the facility sensors are 4-20 mA transmitters. Use of the USCA amplifier however, would minimize the value of using transmitters.
- IEEE-485 to Allen-Bradley ControlNet [8] gateway located in the test-stand signal control building to interface with resident PLC's.

KSC is undertaking a number of USCA modifications as well, that may include:

- Development of a lower cost USCA with a lower sampling rate and elimination of the dual channel redundancy.
- Development of a lower cost data management system.

Additionally, SSC is considering the implementation of health monitoring through additional software processes that can reside in the USCA, TEDS and/or at the central data concentration point (data management system and above in Fig. 2.)

VI. USCA EVALUATION SUITE

Two test beds have been specified for SSC USCA evaluation. A laboratory configuration has been established to allow initial implementation and validation of the USCA elements. The next stage will be to place USCA elements on a test stand to allow collection of parallel data sets for comparison w/ existing data acquisition environments. The E-3 test stand is a good candidate for this parallel evaluation because it supports the most experimental test articles and serves as a technology demonstrator test bed.

VII. SUMMARY

Stennis Space Center is actively evaluating and developing methods for reducing DAS costs and improving system reliability. On the hardware side, Kennedy's USCA architecture offers many advantages including flexible data acquisition services with improved quality assurance for lower cost. This can be further enhanced with a gateway to the existing Allen-Bradley control system. On the software side, qualitative processing theories are excellent candidates to embed distributed intelligence at the sensor level, process level, and overall system level, to support intuitive, fast, and reliable monitoring, diagnostics, and health management of test stands and supporting systems.

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Authors

Contact Author

Family (Last) Name: Figueroa
Given (First) Name: Fernando
Organization/Company: NASA Stennis Space Center
Full Mailing Address: NASA Stennis Space Center, Code VA34, Building 8306, Stennis Space Center, MS 39529-6000, USA
Phone: (228)688-2482
Fax: (228)688-1106
E-Mail: fernando.figueroa@ssc.nasa.gov

Co-author (fill in for EVERY co-author)

Family (Last) Name: Schmalzel
Given (First) Name: John
Organization/Company: Rowan University
Full Mailing Address: Rowan University, Department of Electrical and Computer Engineering, Glassboro, NJ, USA
Phone:
Fax:
E-Mail:

Co-author (fill in for EVERY co-author)

Family (Last) Name: Solano
Given (First) Name: Wanda
Organization/Company: NASA Stennis Space Center
Full Mailing Address: NASA Stennis Space Center, Code VA34, Building 8306, Stennis Space Center, MS 39529-6000, USA
Phone: (228)688-2655
Fax: (228)688-1106
E-Mail: Wanda.Solano@ssc.nasa.gov

Co-author (fill in for EVERY co-author)

Family (Last) Name: Thurman
Given (First) Name: Charles
Organization/Company: NASA Stennis Space Center
Full Mailing Address: NASA Stennis Space Center, Code VA34, Building 8306, Stennis Space Center, MS 39529-6000, USA
Phone: (228)688-7680

Fax: (228)688-1106
E-Mail: Chuck.Thurman@ssc.nasa.gov

Name of the Person intending to present the paper: Fernando Figueroa

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